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Test Platform for Photovoltaic Systems with Integrated Battery Energy Storage Applications

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***Abstract* — We present a hybrid simulation and a real-time test platform for developing control systems for photovoltaic (PV) inverters with integrated battery energy storage (BES). The platform consists of a dual-stage single-phase PV inverter system, DC coupled with a full-bridge grid connected inverter, which emulates the charge regulator and battery bank. The real-time control of the two power electronic converters is implemented in a Simulink/dSpace platform, together with the real-time simulation model of the battery pack. The input power can be provided by either a high performance PV emulator or by a physical PV array. The platform enables real-time testing of PV+BES control systems and energy management systems (EMS), for a variety of battery technologies, which can be modelled in detail and emulated by the full-bridge grid connected inverter. Such flexibility is difficult to achieve with real BES systems, due to electrical safety and cost constrains of high power charge regulators and battery packs.**

***Index Terms* – Battery Emulator, Energy storage, Photovoltaic systems, Test equipment.**

I. INTRODUCTION

The total installed photovoltaic (PV) capacity is estimated to have passed 400 GWp worldwide, at the end of 2017 [1], which although significant, it represents less than two percent from the total electricity demand [2]. To accelerate and support the penetration of PV energy, requires the modernization of the electrical grid, including the deployment of new energy storage systems. Recent policies and incentives aim to increase the application of energy storage for new and existing power plants, but also at household level for increase self-consumption [3]. The prospects of combining PV and storage deployments is predicted to reach 769MW of installed power by the year 2020 [3]. In this regard, integrating PV generation with energy storage can present many opportunities: i) new grid support functions and market participation from large PV plants with active energy reserves; ii) improved self-consumption and lower-energy bill for residential users; iii) support for adoption of electric vehicles.

Integrating battery energy systems (BES) with PV systems, requires development of both lower- and higher-level control functions, such as batterry management systems (BMS) and energy management systems (EMS), specific to the requirements of PV applications [4] . However, researching and testing control systems for such PV+BES systems under realistic operation conditions can be difficult to achieve in practice. First, testing and integrating different battery technologies and capacity sizes, in a PV system, is time consuming and costly. Moreover, battery packs for residential PV applications are in the kWh range [5], and can pose an electrical safety risk. In this situation, battery emulators are ideal for research and development purposes.

Previous research on battery emulators focuses mainly on automotive applications. The growing necessity of installed capacity creates a challenge for research and development of hybrid and electrical vehicles. In addition, the need for reliable tests, performed under the same operating conditions, can be compromised by such changing behavioural devices. One such proposed battery emulator [6] uses lead acid batteries connected to several DC/DC bi-directional converters. Aided by an impedance-based battery model, the system can simulate the behaviour of other battery types.

In [7] a Lithium-ion battery emulator is presented. A bi-directional DC/DC converter serves as a power stage for emulating the battery behaviour, assisted by a non-linear battery model that provides the voltage reference for the converter control.

In [8], [9] a pre-existing unidirectional controlled DC source is converted into a battery emulator capable of two-quadrant operation. The DC source is controlled via a circuit-based battery model, allowing power hardware in the loop (PHIL) testes.

In [10], [11] a battery emulator based on three interleaved step-down DC/DC converters is presented. A Model Predictive Control (MPC) based design, is applied for control of the converter. Furthermore, the battery model is based on local model network (LMN) approach and a robust impedance control is applied.

Very commonly, PV and BES systems are coupled via a DC connection, as shown in Fig. 1. They are typical in residential PV [12] and electric vehicle applications, such as the Tesla Powerwall 2 [13].

As can be observed in Fig. 1, the system consists of: i) a PV voltage boost stage responsible for the PV MPP tracking; ii) an inverter stage implementing the grid connection and DC link voltage control; iii) and a bi-directional DC/DC charge regulator of the battery pack, implementing the BMS and EMS control.

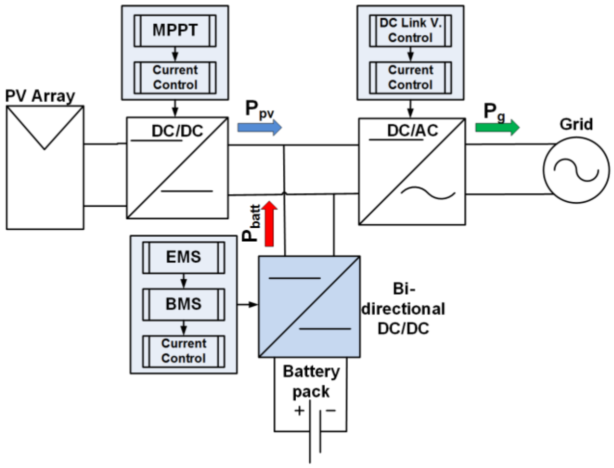

Fig. 1. Generic PV system integrated with a DC coupled BES showing the main control functions.

In this work, we propose to emulate the DC/DC charge regulator with a grid connected full-bridge AC/DC converter shown in Fig. 2. This converter is capable of bi-directional power flow modelling the charge and discharge of the battery.

Moreover, a battery model implemented in the dSpace controller of the full-bridge converter, simulates in real-time the static and dynamic response of the battery pack.

The battery emulator is then integrated/DC coupled into a dual-stage single-phase PV inverter test system, which was previously developed [14].

This platform allows for power hardware-in-the-loop tests (PHIL) for different solar irradiance and temperature profiles, different PV module types and array sizes, as well as different battery sizes and technologies.

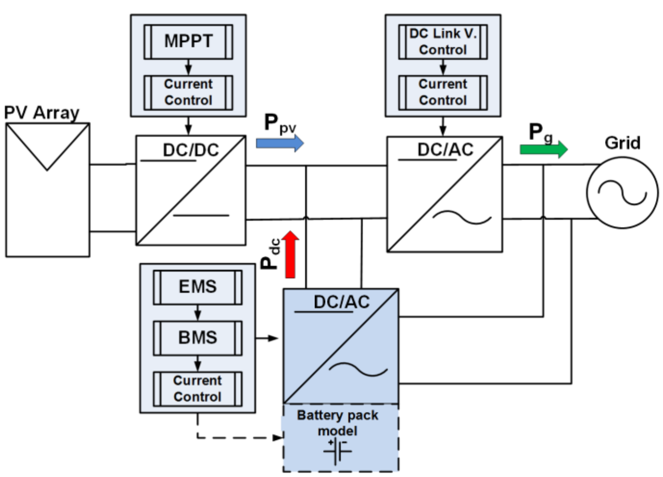

Fig. 2. Proposed PV system + BES emulator platform - based on a grid connected full-bridge inverter.

II. PV+BES System Modelling

A. Models and simulation of the PV + BES systems

To verify the operation of the full-bridge converter emulating the charge regulator and the battery pack, the two PV+BES systems from Fig. 1 and Fig. 2 where first simulated in Simulink/PLECS environment. A case study of a BESS system for power smoothing is considered. This is in fact a common application for BESS systems due to the unpredictability of PV generation. Under this circumstances, the battery provides or absorbs power based on a control signal that is first smoothened by a filter [15].

The simulation model is composed of a PV array model based on the four-parameter Shockley diode equations and parametrized from the datasheet in [16], corresponding to a 0.9 kWp BPMSX120 PV string. A dual stage PV inverter consisting of a boost converter and a single-phase/full-bridge inverter, which are implemented as average converter models, the same for the bi-directional charge regulator of Fig. 1 and the full-bridge grid connected inverter operating as battery emulator of Fig. 2. The grid-connected inverters are identical, and are parametrized after Danfoss FC302 VLTs, rated at 2.2 kW. The battery pack model was implemented based on the empirical model for Li-Ion batteries presented in [17], which follows Shepherd's equation for battery voltage estimation [18]. The battery pack consists of 61 series connected battery cells, with a capacitance per cell of 2.1Ah (see Table 1).

The DC link voltage and current controllers for the single-phase inverters were implemented based on Proportional Integral (PI) and Proportional Resonant (PR) controllers, as described in [19] , whereas the maximum power point tracking (MPPT) was implemented based on the Perturb & Observe (P&O) method [20]. To regulate the charge and discharge of the battery pack the filtered PV power, aided by a 1st order low pass filter with time constant of 5 seconds, is used as power reference.

B. Simulation Results

The operation of the full PV + BES system of Fig. 1 and Fig. 2 was simulated for a trapezoidal solar irradiance profile (shown in red - from 600 to 1000 W/m^2 with a slope of 400 W/m^2/s) with an abrupt change of 200 W/m^2 for 0.5 seconds, simulating fast moving clouds. The system was simulated for constant 46°C module temperature, close to the nominal operating conditions in a summer day.

In Fig. 3 the power flow simulation of the two systems is presented, where: P_{pv} (shown in dashed blue) represents the power generated by the PV array.

As can be observed, from 3.5 to 8 seconds, the MPPT is not extracting the maximum power from the PV array, since the irradiance profile just changed from 600 to 1000 W/m^2. However, after 8 seconds, the MPPT has locked on the PV array's maximum power point (MPP).

The P_{batt} (magenta) represents the battery pack charge/discharge power profile, where positive power values signify battery discharging. P_g (green) represents the total power transferred to the grid by the PV BES system. Whereas P_{dc} (black) represents the power transferred to and from the DC link by the battery emulator/grid converter.

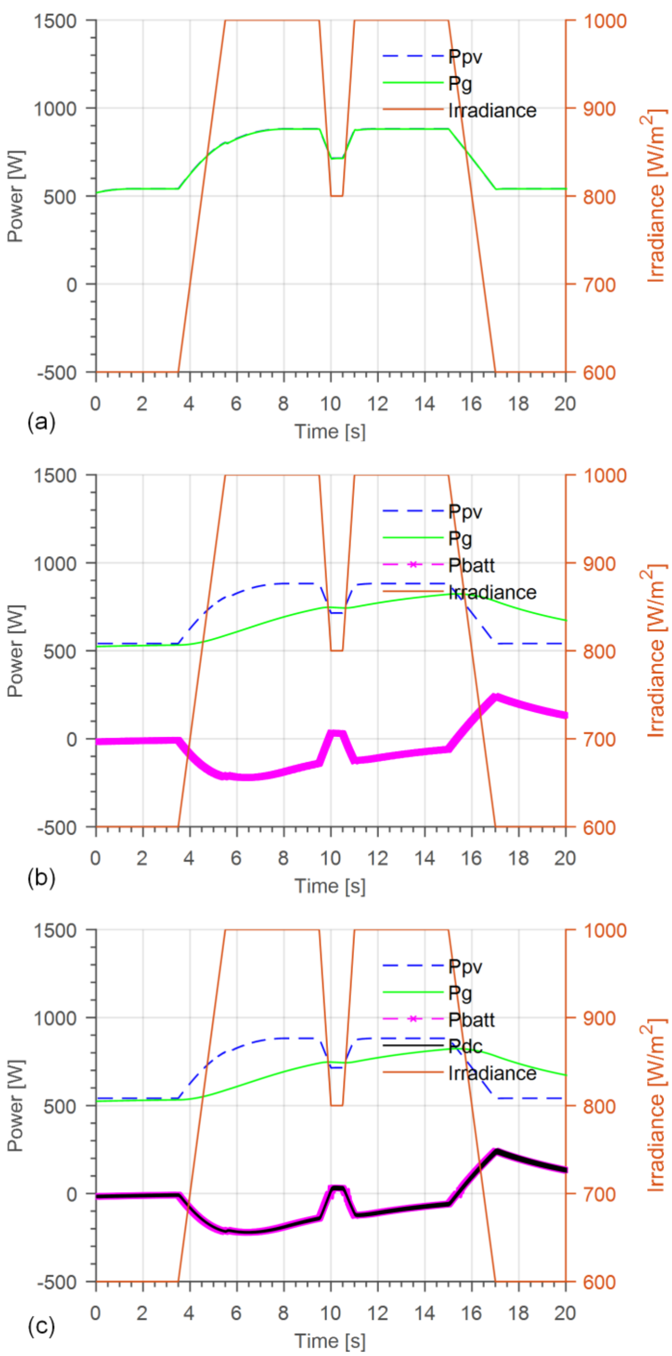

Fig. 3. Power flow simulation of: (a) system without BES; (b) PV+BES system of Fig. 1; (c) PV+BES emulator of Fig. 2, for a changing irradiance profile.

In Fig. 3 (a), a control test is first performed to illustrate the impact on the grid power of the fast change in irradiance.

This serves as a comparison for Fig. 3 (b) and (c), which corresponds to the cases of Fig. 1 and Fig. 2, where a BES system is employed. It can be observed that from 9.5 to 11 seconds the reduction of 200 W/m^2 in irradiance, originated a reduction in the delivered power of 167W. In addition, as no power losses are considered, the P_{pv} generated matches the grid power. However, on the same time interval of Fig. 3 (b) and Fig. 3 (c) the implemented BES systems are capable of compensating the power drop, thus they smoothen the grid power. Moreover, the two systems have a nearly identical operation, with the battery emulator – P_{dc} in Fig. 2, being capable of replicating the operation of the BES - P_{batt} in Fig. 1.

The simulation results suggest that the BES can be emulated by a full/bridge grid connected inverter, and further analysis can be performed in the hardware implementation of the test platform.

III. Experiment Setup

The experimental procedure consists of three different tests that aim to validate and illustrate the versatility of the proposed battery emulator. The experimental test setup, shown in Fig. 4, consists of an 800W DC/DC boost converter and two back-to-back connected 2.2kW Danfoss VLT-FC302 inverters, connected to the grid through LC filters and a 1:1 transformer. One of the converters will operate in PV inverter mode, whereas the other as a battery emulator.

The control system has been implemented in Simulink and runs in real-time on the dSpace 1103 controller board. The boost converter control is implemented on a Texas Instruments TMS320F335 digital signal processor.

The PV input of the system can be connected to a 1000V/40A high bandwidth PV simulator with a linear post-processing unit, or directly to a 0.8kWp PV string. The PV inverter functionality of the PV systems has been implemented and tested previously [14].

For the first and second experimental tests, a 3.3V Li-Ion battery with 61 cells in series and a capacity per cell of 2.1Ah was considered. As for the third test, a 2V lead acid battery with 60 cells in series and a capacity per cell of 7.2 Ah, is also considered. More details about the implemented batteries can be found on Table 1.

Table 1: Battery Parameters

	Battery Type	
Parameters	Lead Acid	Li-Ion
E0 [V]	124.6	203.4
R [Ω]	0.4	0.12
Q [Ah]	7.2	2.12
K [Ω]	0.47	0.06
A [V]	8.3	4.28
B [A/h]	125	12

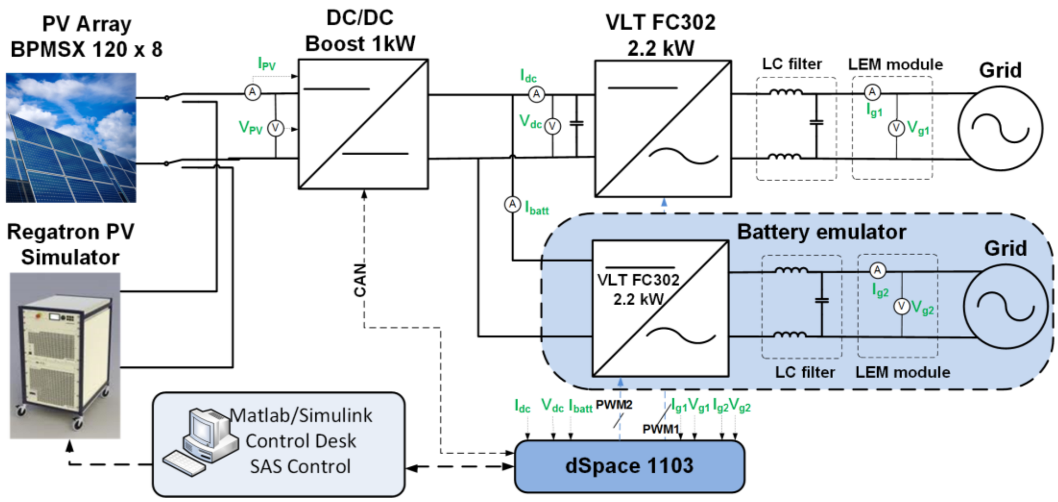

Fig. 4. Photovoltaic System Test Platform with Integrated Battery Energy Storage Emulator.

C. Test 1: Operation of the proposed emulator for smoothing the grid power

In the first test, the performance of the battery emulator, operating for PV power smoothing, is analysed and compared with the simulation results from Fig. 3. The test is performed under the same conditions of temperature and irradiance and for the same battery model [17]. The Regatron PV simulator, shown in Fig. 4, is programmed with the same PV array parameters and irradiance profile used in the simulation, and connected to the PV+BES emulator.

As mentioned, a first test, Fig. 5 (a), is used as control to compare the system with and without BES. Looking at Fig. 5 (a) and Fig. 5 (b) it is evident the capability of the BES in smothing the grid power. Moreover, since this is a single-phase system higher DC-link capacitance is required for its operation. This can significantlly constrain the capability of the system in emulating the fast charge/discharge profile of the battery pack.

The experimental result of Fig. 5 (b), for a step irradiance dip, with a slope of ± 400 W/m^2/s, prove that the proposed emulator is fast enough in compensating the power fluctuations. This further validates the applicability of the AC/DC converter in operating as a battery emulator. Also by comparing the simulation of Fig. 3 (b) and Fig. 3 (c) with the experimental results of Fig. 5 (b) a nearly identical operation is obtained.

D. Test 2: Battery Models comparison

The second test consists of a comparison of three different Li-Ion battery models: the previously used empirical model (EM) [17], the Thevenin based model (TM) [21] and a general power/efficiency model (ESM). The three battery models were subject to the same charge /discharge profile of ± 500W with a pulse width of 600 seconds for a test duration of 1500 seconds.

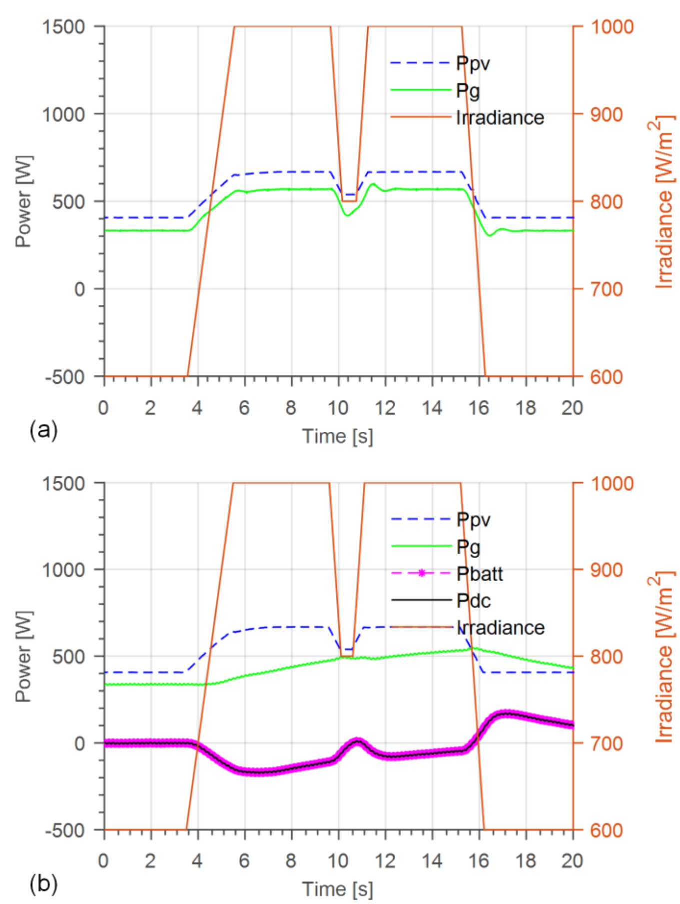

Fig. 5. Power flow experiment of: (a) system without BES; (b) PV+BES emulator of Fig. 2, for a changing irradiance profile.

As can be observed from Fig. 6 the system can emulate the basic features of each battery model type. When comparing the dynamic behaviour, both at discharge (left) and charge (right) conditions, the superior performance of TM models is evident. Due to the presence of the RC network, the TM can predict better the dynamic voltage response of the battery, to a current excitation. Nevertheless, the simpler EM, also important for battery simulation and with simpler parameter extraction, prove to be properly emulated.

As for the SOC estimation, presented in Fig. 6, the EM model presents slower response when compared to TM and ESM based models. In fact, the difference between the EM model and the fastest response model (ESM) is about 8.6% and 5.7% for discharge and charge respectively.

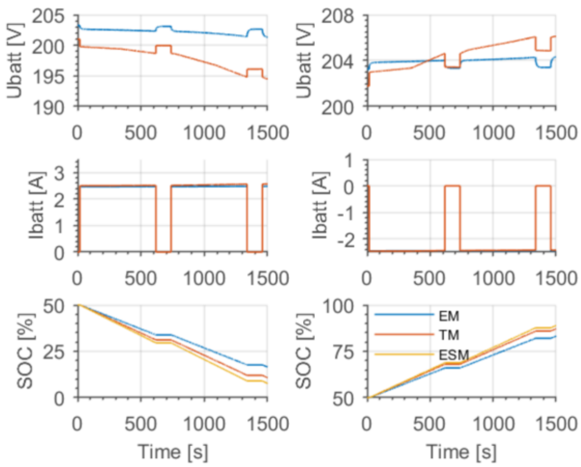

Fig. 6. Experimental dynamic discharge (left) / charge (right) of the EM (blue), TM (red) and EMS (yellow) emulated battery models and SOC estimation, for a charge/discharge profile of ±500W for 600 seconds.

E. *Test 3: Li-Ion vs Lead Acid*

The third test presents an analogy between two different battery technologies: Li-Ion (Li) and Lead Acid (LA). For this test, the charge/discharge profile from test 2 is again applied and the previous empirical battery model [17], was used and adapted for both technologies.

In Fig. 7, the dynamic charge and discharge profile of the two battery technologies is presented. It can be observed that the battery voltage of the LA battery decays at a faster rate than the Li. This is one of the main differences of the Li when compared to LA, due to the higher resistance of LA batteries. This feature has a direct effect on the battery current. Since the batteries are controlled by their power, a reduction in the battery voltage will result in an increase in the current; this is again observed in Fig. 7. As for the SOC, a direct relation is difficult to be established as the batteries have different capacities and are charged with different C-rates.

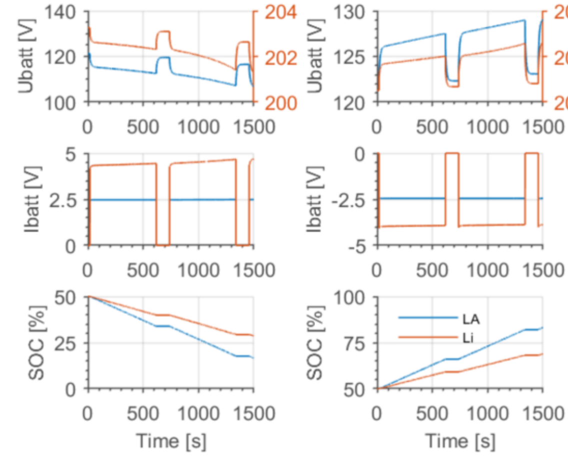

Fig. 7. Experimental dynamic discharge (left) / charge (right) of the Lead Acid (blue) and Li-Ion (red) emulated battery models and SOC estimation, for a charge/discharge profile of ±500W for 600 seconds.

IV. CONCLUSION

In this work, we proposed a test platform for safe and cost-effective-real-time implementation and testing of PV+BES applications for different battery technologies and storage sizes. The case scenario of a BES smoothing the PV oscillations was used to illustrate through simulation models and experimental implementation, that a full-bridge grid connected inverter can operate as a battery emulator for PV+BES applications. Furthermore, three battery models of different complexity and two battery technologies were tested to further illustrate the versatility of the proposed emulator.

This solution, when compared to previously presented DC/DC counterparts, allows for higher power density and reduced cost. This system also allows full freedom of customization, being possible to implement virtually all types of battery models for a variety of technologies and chemistries, something usually not possible in most commercial battery emulators.

Future research intends to better assess and understand the performance of the battery emulator when dynamic real-life mission profiles are considered.

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